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An Experimental Study on Surface Wave Interactions with Viscoelastic Boundaries

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ABSTRACT

Recently, we performed an experimental study on wave interactions with floating viscoelastic covers that represent the varying sea ice conditions (Sree et al., 2016). In the present study, we continued to examine the wave interactions with a viscoelastic cover including the presence of a viscoelastic bottom in the laboratory. The topic has relevance in the port planning related to future Arctic shipping. The wave interactions with mud had been investigated earlier theoretically by MacPherson (1980), Hsiao and Shemdin (1980), Maa and Mheta (1990) and many others. However, no experimental verification of the theories using a homogeneous viscoelastic bottom has been reported in the literature, as far as we are aware. Our experimental approach utilized oil-doped PDMS (Polydimethylsiloxane) and glycerol-doped PDMS to create the top and bottom viscoelastic boundaries, respectively. Wave flume experiments with the viscoelastic boundaries were then performed in shallow water conditions. The surface wave profiles were measured using ultrasound sensors, and the changes in wave speed and wave height were compared to the reference condition of a rigid bottom. It was found that the wave length was modulated with the viscoelastic boundaries, and the attenuation of wave height along the region was different with and without the bottom layer. The results of the analysis shall be presented in the conference.

Keywords: viscoelastic material; floating cover; bottom layer; wave interaction

INTRODUCTION

Surface waves in the Arctic region experience the modulation in wavelength and attenuation in wave amplitude in the presence of ice covers and muddy bottoms, particularly in shallow waters. The analysis of three-layer system with ice covered shallow waters and muddy bottom, is necessary for port planning purposes in the Arctic region. It enables the determination of how the waves would transform near the port structures.

For wave attenuation with ice covers, both field studies and laboratory experiments had shown that the wave amplitude decays exponentially with distance (Wadhams et al., 1988; Newyear and Martin, 1999). The rate of decay depends on factors such as the thickness of the ice layer, its density, concentration as well as the size of ice floes. Many theoretical models had also been developed, the most generalized model of all ice types is the viscoelastic model (Squire and Alan, 1980; Robinson and Palmer, 1990 and Wang and Shen, 2010). The recent wave-ice experiments by Zhao and Shen (2015) showed that the viscoelastic model by Wang and Shen (2010) fit well for different types of ice covers.

The bottom mud also plays an important role in modulating the surface waves in the coastal regions (Jiang and Mehta, 1995, 1996; Mathew and Baba, 1995). Many theoretical studies had been performed modelling the mud as elastic, viscous as well as viscoelastic bottoms (MacPherson, 1980; Hsiao and Shemdin, 1980; Maa and Mehta, 1990). The related laboratory studies (Maa and Mehta, 1990; Zhao et al., 2006; Winterwerp et al., 2007) showed that the attenuation of wave height along the muddy bottom is frequency dependent. To the authors' knowledge, experiments on wave propagation over a homogeneous viscoelastic bottom have not been reported so far. This study focuses on the interactions of surface waves with different boundary conditions: viscoelastic cover only, viscoelastic bottom only, and a three-layer system with both viscoelastic boundaries.

MATERIAL PREPARATION AND EXPERIMENTAL PROCEDURES

The viscoelastic floating cover was made of oil-doped PDMS (Polydimethylsiloxane) as reported in Sree et al. (2016). The thickness of the cover was 1.0cm. The preparation included the mixing of the components (base, curing agent and white oil), degassing (to remove the trapped air bubbles) and curing. The mass percentage of the oil and curing agent used for the cover in the present study were 30% and 4%, respectively. Subsequently, the curing of the PDMS cover was conducted in a 2.0m long stainless steel tray for 7 days at 25^{o}C.

The procedures for the preparation of the viscoelastic bottom were identical as the cover, except that the white oil was replaced with glycerol which is denser than water. The thickness of the bottom cover was 2.0cm. The mass percentage of the glycerol and curing agent used for the bottom were 10% and 2% respectively, and the curing was conducted in the 2.0m long stainless steel tray for a longer period of 15 days at 25^{o}C. It should be noted that the rheological properties of the cover as well as the bottom can be varied by changing the mass percentage of curing agent, m_{CA} added at the time of preparation.

The rheological properties of the viscoelastic covers and bottoms were quantified using a rheometer (Anton Paar MCR 302, Germany) with parallel plate geometry (PP20). The rheometer tests included: (i) amplitude sweep, to determine the linear viscoelastic regime and (ii) frequency sweep, to determine the variation of storage modulus (G') and loss modulus (G'') with frequency of oscillation (ω) (Sree et al., 2016). The range of frequency of oscillation was determined by comparing with the required angular frequency ($\omega = 2\pi/T$). The variation of G' and G'' with ω of the viscoelastic cover and bottom are shown in Figure 1.

The experiments were conducted in a progressive wave flume at the Environmental Process Modelling Centre, NEWRI, Singapore. The flume was made of transparent tempered glass supported by stainless steel framework (8.0 m long, 0.30 m wide and 1.0 m deep). It was equipped with a paddle type wave generator at one end, and a dissipating beach made of wire mesh at the other end. The shallow water depth was set by allowing the viscoelastic bottom to rest on a raised platform (Figure 2).

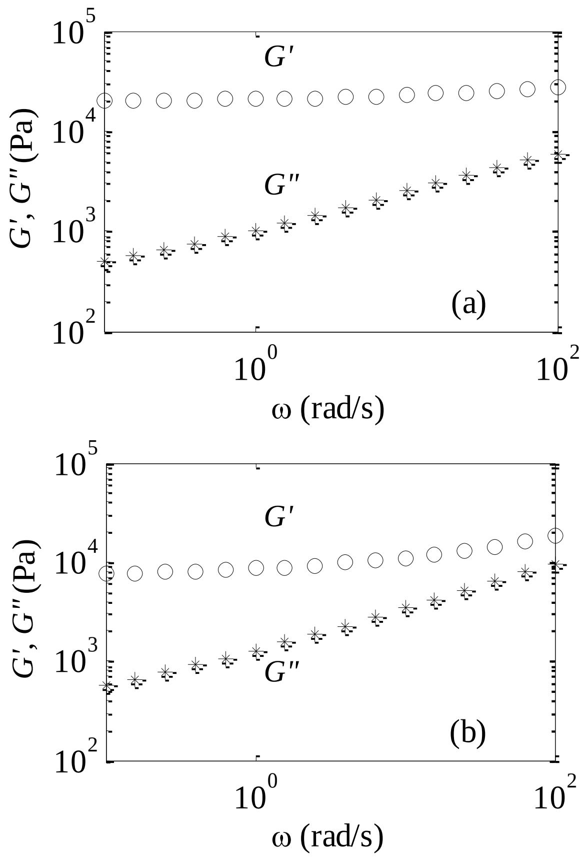

Figure 1. Viscoelastic properties against angular frequency for the (a) PDMS cover and (b) PDMS bottom. Circles = G' and asterisk =G''.

In the present study, the wave period was fixed at T = 0.7s, and the water depth above the viscoelastic bottom was 6.0cm. The wave height was set at 1.7cm. A capacitance wave gauge (WG_c) was installed near the wave maker that gave feedback to control the generation of the required wave profile.

Seven ultra sound sensors were installed along the length of the flume (Figure 2) to monitor the vertical surface displacement due to the progressive waves. The ultrasound sensor, US1, was kept at 20cm from the leading edge of the platform. All other ultrasound sensors, named in sequential order, were at 20cm interval from each other. Four resistance wave gauges were also installed near the wave generator to measure any possible reflection caused by the platform, viscoelastic bottom as well as viscoelastic cover. The sensors and wave gauges were connected to a data acquisition system, and the synchronized data were obtained through the LABVIEW software.

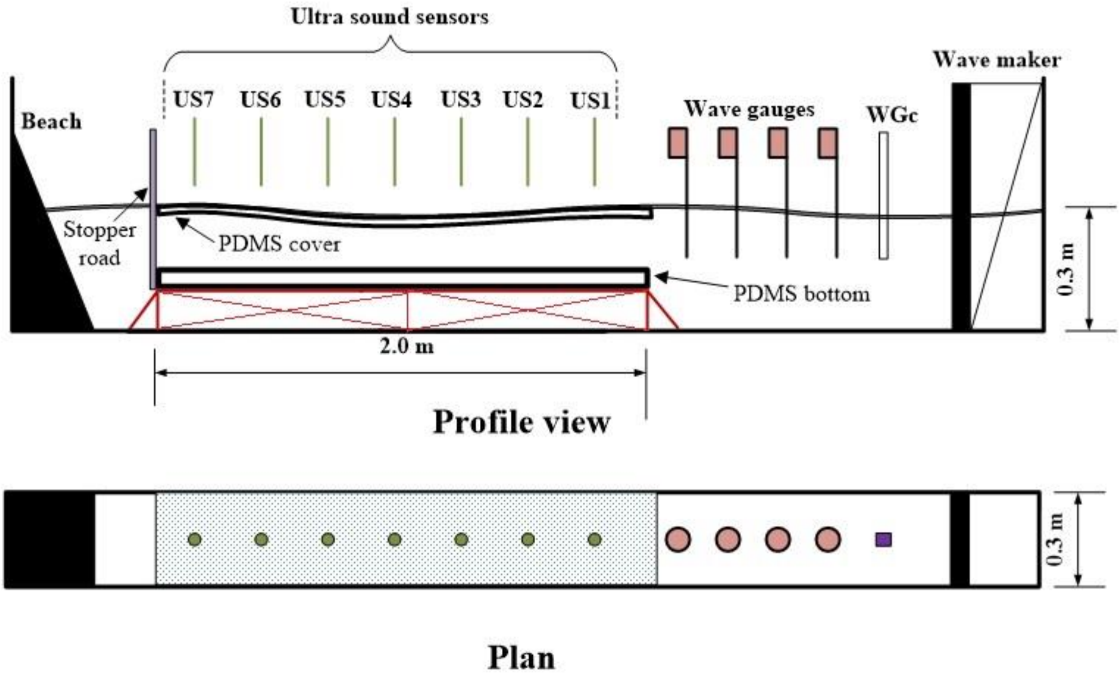

Figure 2. Schematic diagram of wave flume with viscoelastic boundaries.

RESULTS

The raw data acquired from LABVIEW was at 50 Hz, which was later increased to 200 Hz by interpolation using the *PCHIP* function in MATLAB (Figure 3). The location and value of peaks (crests) were then identified using the *findpeaks* function of MATLAB. Only the first three fully developed waves were considered for the analysis in order to avoid the effect of beach reflection.

The wave celerity in the viscoelastic region was determined by calculating the time taken for each of the fully developed waves to travel past the ultra sound sensors along the cover (Sree et al., 2016). The variation in celerity along the region is shown in Figure 4. The figure shows that the wave speed decreased with the presence of the viscoelastic boundaries. The wavenumber and attenuation coefficient obtained are shown in Table 1. The attenuation coefficient was determined by fitting an exponential curve ($\eta_a = \eta_0 \, e^{-\alpha x}$) to the measured data as illustrated in Figure 5. The attenuation coefficient obtained for different boundary conditions are provided in Table 1.

Overall, the experimental results showed that both the wavenumber and wave height were modulated by the presence of viscoelastic boundaries (Table 1). With the viscoelastic floating cover only, the wave attenuation increased significantly as expected, and wave length shortening was observed. With the viscoelastic bottom only, however, the attenuation reduced instead when compared to open water with a rigid bottom, while the wave length was preserved. With both, the effects were almost combined linearly.

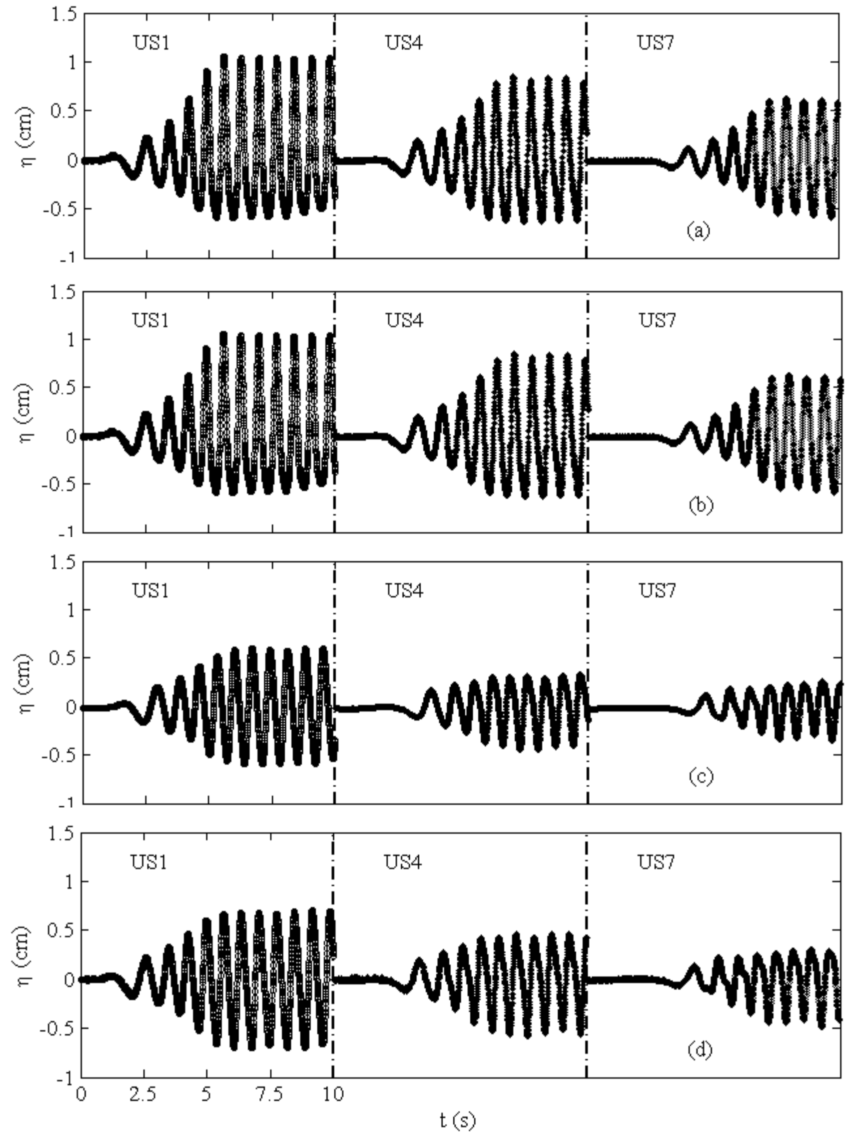

Figure 3. Time series of the wave record for US1, 4 and 7: (a) open water with rigid bottom, (b) viscoelastic bottom only, (c) viscoelastic cover only and (d) both viscoelastic cover and bottom.

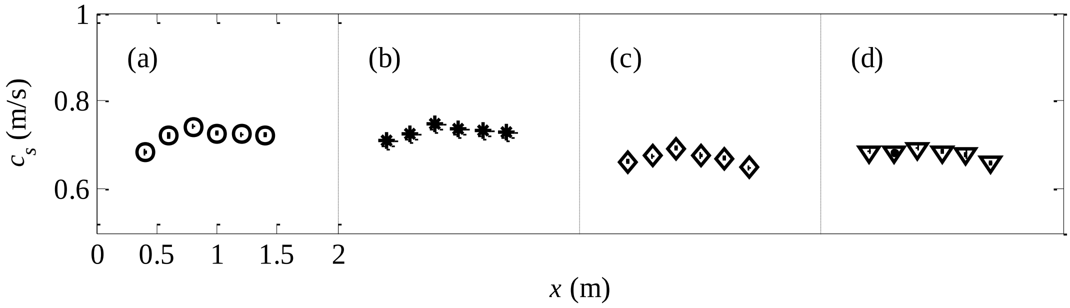

Figure 4. Celerity along the viscoelastic boundary region: (a) open water with rigid bottom, (b) viscoelastic bottom only, (c) viscoelastic cover only and (d) both viscoelastic cover and bottom.

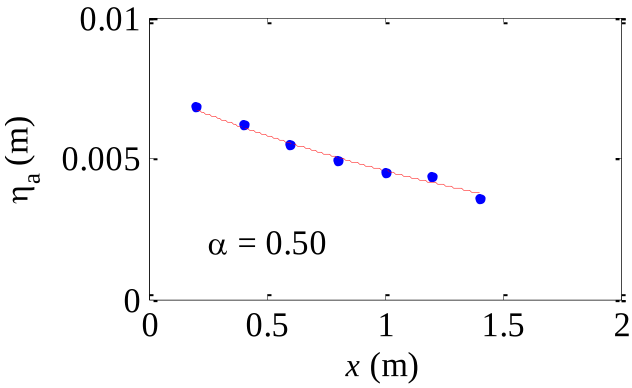

Figure 5. Wave amplitude along the region with both viscoelastic boundaries.

Table 1. Wave number and attenuation coefficient for different boundary conditions (T=0.7s)

Case	k (rad/m)	α (1/m)
Open water with rigid bottom	12.3	0.23
Viscoelastic bottom only	12.2	0.18
Viscoelastic cover only	13.3	0.56
Both viscoelastic boundaries	13.2	0.50

CONCLUSION

The present results thus demonstrated the feasibility of adopting the experimental approach with oil-doped and glycerol-doped PDMS materials to quantify the wave interactions with viscoelastic boundaries in the laboratory. We are currently conducting further experiments to cover a broader range of wave and viscoelastic characteristics.

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